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Direct Measurements of  $V_{tb}$ WOLFGANG WAGNER<sup>1</sup>

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The measurement of the single top-quark production cross section in hadron collisions at the Tevatron and the LHC can be used to determine the absolute value of the CKM matrix element  $V_{tb}$  without assuming the unitarity of the CKM matrix. By measuring the branching ratio of the decay  $t \rightarrow W + b$  one can relate  $V_{tb}$  to the matrix elements  $V_{ts}$  and  $V_{td}$ . The current experimental status and future prospects of these measurements are reviewed.

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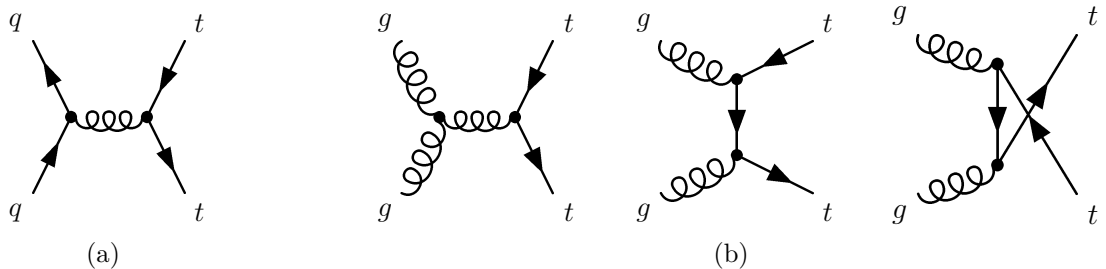


Figure 1: Feynman diagrams of the leading order processes for  $t\bar{t}$  production: (a) quark-antiquark annihilation ( $q\bar{q} \rightarrow t\bar{t}$ ) and (b) gluon-gluon fusion ( $gg \rightarrow t\bar{t}$ ).

## 1 Introduction

The main source of top quarks at the Tevatron is the pair production via the strong interaction. At leading order in perturbation theory ( $\alpha_s^2$ ) there are two processes that contribute to  $t\bar{t}$  production, quark-antiquark annihilation  $q\bar{q} \rightarrow t\bar{t}$  and gluon-gluon fusion  $gg \rightarrow t\bar{t}$ . The corresponding Feynman diagrams for these processes are depicted in Fig. 1. At the Tevatron the  $t\bar{t}$  cross section is dominated by  $q\bar{q}$  annihilation processes contributing 85%, while only 15% of  $t\bar{t}$  pairs are produced via  $gg$  fusion. At the LHC at  $\sqrt{s} = 14$  TeV, the situation is reversed, 90% of  $t\bar{t}$  events are produced by  $gg$  fusion processes and only 10% by  $q\bar{q}$  annihilation. The reason for this phenomenon is the very different parton luminosities at partonic energies above the  $t\bar{t}$  threshold. Due to the higher center of mass energy at the LHC it is possible to produce  $t\bar{t}$  pairs already at lower  $x$  of the incoming partons where the gluon parton density dominates over the quark densities. In addition, the Tevatron features antiquarks as constituent quarks of the antiproton leading to a considerable large antiquark density at large  $x$ . The cross sections for  $t\bar{t}$  production are predicted [1] to be

$$\sigma_{\text{LHC}} = (887_{-33}^{+9} (\text{scale})_{-15}^{+15} (\text{PDF})) \text{ pb} \quad (\text{at } 14 \text{ TeV}), \quad (1)$$

$$\sigma_{\text{Tev}} = (7.04_{-0.36}^{+0.24} (\text{scale})_{-0.14}^{+0.14} (\text{PDF})) \text{ pb} \quad (\text{at } 1.96 \text{ TeV}). \quad (2)$$

According to the standard model (SM) top quarks decay with a branching ratio of nearly 100% to a bottom quark and a  $W$  boson and the  $t\bar{t}$  final states can be classified according to the decay modes of the  $W$  bosons. The most important (or golden) channel is the so-called *lepton+jets* channel where one  $W$  boson decays leptonically into a charged lepton (electron or muon) plus a neutrino, while the second  $W$  boson decays into jets. The lepton+jets channel features a large branching ratio of about 29%, manageable backgrounds, and allows for the full reconstruction of the event kinematics. Other accessible channels are the *dilepton* channel, in which both  $W$  bosons decay to leptons, and the *all-hadronic* channel, where both  $W$  bosons decay hadronically. The dilepton channel has the advantage of having a low background,

$W$ decays	$e/\mu\nu$	$\tau\nu$	$q\bar{q}$
$e/\mu\nu$	5%	5%	29%
$\tau\nu$	–	1%	15%
$q\bar{q}$	–	–	46%

Table 1: Categories of  $t\bar{t}$  events and their branching fractions. The sum of all fractions is above 100% because of rounding effects.

but suffers on the other hand from a lower branching fraction (5%) compared to the lepton+jets channel. The all-hadronic channel, on the contrary, has the largest branching ratio of all  $t\bar{t}$  event categories (46%), but has the drawback of a huge QCD multijet background, that has to be controlled experimentally. The different categories of  $t\bar{t}$  and their branching fractions are summarized in Table 1.

## 2 Top-antitop Cross Section Measurements

The most precise  $t\bar{t}$  cross section measurements are obtained in the lepton+jets channel based on analyses in which the background is controlled either by the identification of the  $b$ -quark jets or by exploiting kinematic or topological information, see for example [2]. The experimental signature of lepton+jets  $t\bar{t}$  events comprises a reconstructed isolated lepton candidate, large missing transverse energy ( $\cancel{E}_T$ ) and at least four jets with large transverse energy  $E_T \equiv E \cdot \sin \theta$ . Two jets originate from  $b$ -quarks. Typical selection cuts ask for a charged lepton with  $p_T > 20$  GeV/ $c$ ,  $\cancel{E}_T > 20$  GeV, and at least four jets with  $E_T > 20$  GeV and  $|\eta| < 2.0$ , one of them identified as a  $b$ -quark jet. The most commonly used algorithm to identify  $b$ -quark jets is based on the reconstruction of secondary vertices in jets, exploiting the relatively long lifetime of  $b$ -hadrons and a large Lorentz boost. The typical decay length of  $b$ -hadrons in high- $p_T$   $b$ -quark jets is on the order of a few millimeters. The requirement of a secondary vertex within one of the jets leads to a large reduction of the  $W$ +jets background by roughly a factor of 50, while the selection efficiency for  $t\bar{t}$  events is about 50% to 60%.

The most recent CDF analysis based on secondary vertex  $b$  tagging [3] is a counting experiment in which the background rate is estimated using a combination of simulated events and data driven methods. The signal region is defined as the data set with a leptonic  $W$  candidate plus  $\geq 3$  jets. To further suppress background, a cut on the sum of all transverse energies  $H_T > 230$  GeV is applied. The jet multiplicity distribution of the  $W$ +jets data set observed by this CDF analysis is shown in Figure 2. The uncertainty on the luminosity measurement is reduced by measuring the ratio of  $t\bar{t}$ -to- $Z$ -boson cross sections and the measured cross section is found to be  $7.32 \pm 0.36$  (stat)  $\pm 0.59$  (syst)  $\pm 0.14$  (Z theory) pb, assuming  $m_t = 172.5$  GeV/ $c^2$ . The

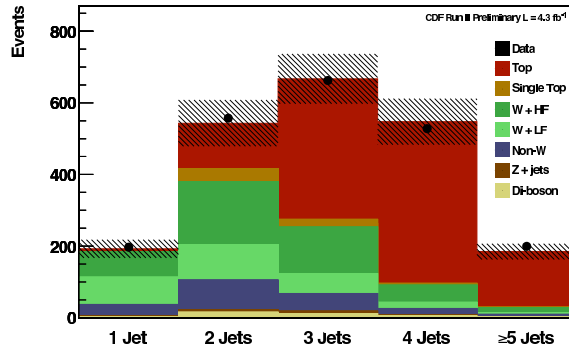


Figure 2: Jet multiplicity distribution for the  $W$ +jets data set, where the  $W$  boson is reconstructed in its leptonic decay  $W^\pm \rightarrow \ell^\pm \nu_\ell(\bar{\nu}_\ell)$ . A cut on  $H_T > 230$  GeV was applied. The analyzed data set corresponds to  $4.3 \text{ fb}^{-1}$  of CDF data.

cross section of  $t\bar{t}$  production and  $Z/\gamma^* \rightarrow \ell^+\ell^-$  production are measured in data samples corresponding to the same integrated luminosity. By forming the ratio of both measured cross sections and multiplying by the well-known theoretical  $Z/\gamma^* \rightarrow \ell^+\ell^-$  cross section the luminosity uncertainty of 6% is effectively removed and replaced by the uncertainty on the  $Z/\gamma^*$  cross section of 2%. In a similar measurement the DØ collaboration measured  $\sigma_{t\bar{t}} = 7.93^{+1.04}_{-0.91} \text{ pb}$  [6].

Recently, the first observations of  $t\bar{t}$  pairs produced at the LHC have been made by the ATLAS and CMS collaborations [4, 5]. The measured  $t\bar{t}$  cross section at  $\sqrt{s} = 7 \text{ TeV}$  is  $\sigma_{t\bar{t}} = 145 \pm 31 \text{ (stat)}^{+42}_{-27} \text{ (syst)} \text{ pb}$  and  $\sigma_{t\bar{t}} = 194 \pm 72 \text{ (stat)} \pm 24 \text{ (syst)} \pm 21 \text{ (lumi)} \text{ pb}$ , respectively.

### 3 The measurement of $\mathcal{R}_b$

In the SM the top quark is predicted to decay to a  $W$  boson and a  $b$  quark with a branching fraction  $\mathcal{R}_b \equiv \text{BR}(t \rightarrow Wb)$  close to 100%. This prediction is obtained in the following way. In general, the top quark can decay in three channels  $t \rightarrow d/s/b + W^+$  and  $\mathcal{R}_b$  is given by the ratio of the squares of the relevant CKM matrix elements:  $\mathcal{R}_b = |V_{tb}|^2 / (|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2)$ . In the SM the CKM matrix has to be unitary ( $\mathbf{V}\mathbf{V}^\dagger = \mathbf{V}^\dagger\mathbf{V} = \mathbf{1}$ ), which leads to  $|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$  and thereby to  $\mathcal{R}_b = |V_{tb}|^2$ . Our present knowledge on  $|V_{tb}|$  stems primarily from measurements of  $b$ -meson and  $c$ -meson decays which determine the values of the other CKM matrix elements. Using the unitarity condition of the CKM matrix one can obtain  $|V_{tb}|$  in an indirect way. This method yields  $|V_{tb}| = 0.999133 \pm 0.000044$  with very high precision [7].

Only recently a determination of  $|V_{tb}|$  without unitarity assumption was obtained

from the measurement of the single top-quark cross section, yielding  $|V_{tb}| = 0.88 \pm 0.07$  [8]. However, if a fourth generation of quarks was present, the unitarity of the  $3 \times 3$  CKM matrix could be violated. Therefore, it is desirable to make a direct measurement of  $\mathcal{R}_b$  using  $t\bar{t}$  candidate events.

In most  $t\bar{t}$  cross section analyses the assumption  $\mathcal{R}_b = 1$  is made, but CDF and DØ have also made two measurements without this constraint [9, 10, 11]. In the latest analysis from DØ [11] the  $W$ +jets data set is split in various disjoint subsets according to the number of jets (0, 1, or  $\geq 2$ ), the charged lepton type (electron or muon), and most importantly the number of  $b$ -tagged jets. The fit results are:  $\mathcal{R}_b = 0.97^{+0.09}_{-0.08}$  and  $\sigma(t\bar{t}) = 8.18^{+0.90}_{-0.84} \pm 0.50$  (lumi) pb, where the statistical and systematic uncertainties have been combined. The lower limit on  $\mathcal{R}_b$  is determined to be  $\mathcal{R}_b > 0.79$  at the 95% C.L. In terms of the CKM matrix elements this result can be summarized by the following relation:

$$|V_{td}|^2 + |V_{ts}|^2 < 0.263 \cdot |V_{tb}|^2 \quad (3)$$

at the 95% C.L. The measurement quoted above is based on a data set corresponding to  $0.9 \text{ fb}^{-1}$ , which is only a small fraction of the available data at the Tevatron. In this measurement the statistical and systematic uncertainties have about the same size. If the an update to the full data set was made, the measurement would be completely systematically limited.

## 4 Measurement of Single-Top Production

While  $t\bar{t}$  pair production via the strong interaction is the main source of top quarks at the Tevatron and the LHC, top quarks can also be produced singly via weak interactions involving the  $Wtb$  vertex. There are three production modes which are distinguished by the virtuality,  $Q^2$ , of the  $W$  boson. The dominant process is the  $t$  channel exchange of a virtual  $W$ , depicted in Fig. 3(a). At the LHC, the subprocess

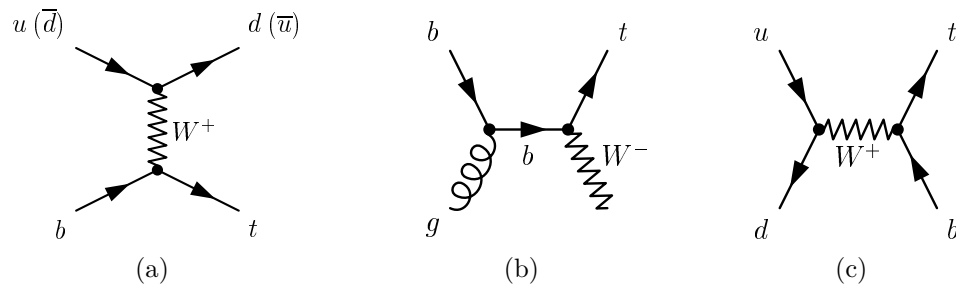


Figure 3: Feynman diagrams of single top-quark production processes. (a)  $t$  channel production, (b) associated  $Wt$  production, and (c)  $s$  channel production.

with the second highest cross section is the associated production of an on-shell  $W$

boson and a top quark, see Fig. 3(b). At the Tevatron,  $Wt$  production has a negligible cross section compared to the other two processes. The Drell-Yan type production of a  $t\bar{t}$ , see Fig. 3(c), has only subleading character at the LHC, but is relevant at the Tevatron.

While Run 1 (1992–1996) and early Run 2 searches for single top quarks at CDF and DØ could only set upper limits on the production cross section [12, 13], analyses using more data and advanced analysis techniques were able to observe singly produced top quarks in March 2009 with a significance of five Gaussian standard deviations [14, 15, 16]. These analyses consider both production modes relevant at the Tevatron,  $t$  channel and  $s$  channel, as one single-top signal, assuming the ratio of  $t$  channel to  $s$  channel events to be given by the SM. This search strategy is often referred to as *combined search*. By measuring the inclusive single top-quark cross section and using theory predictions, one can deduce the absolute value of the CKM matrix element  $V_{tb}$ , without the assumption that there are only three generations of quarks. If one measured  $|V_{tb}|$  to be significantly smaller than one this would be a strong indication for a fourth generation of quarks or other effects beyond the SM [19, 17, 18].

Single top-quark events feature a  $Wb\bar{b}$  ( $s$ -channel) or  $Wbq\bar{b}$  ( $t$ -channel) partonic final state. The most sensitive analyses reconstruct the  $W$  boson originating from the top-quark decay in its leptonic decay modes  $e\nu_e$  or  $\mu\nu_\mu$ , while hadronic  $W$  decays and decays to  $\tau\nu_\tau$  are not explicitly considered, because of large backgrounds from QCD-induced jet production. The quarks from the hard scattering process manifest themselves as hadronic jets with large transverse momentum. Additional jets may arise from hard gluon radiation in the initial or final state. The experimental signature of SM single top-quarks is therefore given by one isolated high- $p_T$  charged lepton (electron or muon), large missing transverse energy ( $\cancel{E}_T$ ), and two or three high- $E_T$  jets, of which one or two originate from a  $b$  or  $\bar{b}$  quark.

The dominating background process is  $Wb\bar{b}$ , followed by misidentified  $W$ +light-quark jet events,  $Wc\bar{c}$ , and  $Wcj$ . In the  $W$ +3 jets data-set  $t\bar{t}$  is the most important background. The total event detection efficiency of single top-quark events is about 2% for the  $t$ -channel process and about 3% for the  $s$  channel. Even though the single top-quark production cross section is predicted to amount to about 40% of the  $t\bar{t}$  cross section, the signal has been obscured for a long time by the very challenging background. After the cut-based event selection sketched above, the signal-to-background ratio is only about 5 to 6%. Further kinematic cuts on the event topology proved to be prohibitive, since the number of signal events in the resulting data set would become too small. Facing this challenge, the analysis groups in both Tevatron collaborations turned to multivariate techniques, in order to exploit as much information about the observed events as possible. The explored techniques comprise artificial neural networks, LO matrix elements, boosted decision trees, and likelihood ratios. All these techniques combine the information contained in several variables into one powerful

discriminant, maximising the separation between the single top-quark signal and the backgrounds. All multivariate analyses see a signal of single top-quark production with significances ranging from 2.4 to 5.2 Gaussian standard deviations. To obtain the most precise result, all analyses of the two collaborations are combined, resulting in a single top-quark cross section of  $2.76^{+0.58}_{-0.47}$  pb (at  $m_t = 170$  GeV/ $c^2$ ) [8].

The measured single top-quark production cross sections can be used to determine the absolute value of the CKM-matrix element  $V_{tb}$ , if one assumes  $V_{tb} \gg V_{ts}$ ,  $V_{tb} \gg V_{td}$ , and a SM-like left-handed coupling at the  $Wtb$  vertex. Contrary to indirect determinations in the framework of flavour physics the extraction of  $|V_{tb}|$  via single top-quark production does not assume unitarity of the CKM matrix and is thereby sensitive to a fourth generation of quarks. The assumption of  $V_{ts}$  and  $V_{td}$  being small compared to  $V_{tb}$  enters on the production side, since top quarks can also be produced by  $Wts$  and  $Wtd$  vertices, and in top-quark decay. The phenomenological analysis of [19, 17] as well as the measurement of  $R_b$ , see 3, indicate that this assumption is well justified. To determine  $|V_{tb}|$  the analysts divide the measured single top-quark cross section by the predicted value, which assumes  $|V_{tb}| = 1$ , and take the square root. Based on the combined cross-section result the Tevatron collaborations obtain  $|V_{tb}| = 0.88 \pm 0.07$  [8].

## 5 Conclusion

Measurements of top-quark production and decay add valuable information to determine or constrain the CKM matrix elements  $V_{tb}$ ,  $V_{ts}$ , and  $V_{td}$ . These experimental constraints are complementary to measurements made with  $b$  and  $c$  hadrons. The measurements of  $R_b$  and the single top-quark cross section lead currently to the constraints

$$|V_{td}|^2 + |V_{ts}|^2 < 0.263 \cdot |V_{tb}|^2 \quad \text{at the 95\% C.L. and} \\ |V_{tb}| = 0.88 \pm 0.07 .$$

In the future it may be possible to also constrain  $V_{ts}$  and  $V_{td}$  in measurements of single top-quark production, even though it will be very challenging to disentangle the different production modes experimentally. At the LHC, single top quarks will be produced in ample numbers, allowing for detailed investigations. However, the priority for the near future will be to establish a single top-quark signal at ATLAS and CMS. Strategies for the analysis of early LHC data have been devised by both collaborations [20, 21].

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